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Research Article

Monitoring land cover dynamics in the Bahr Al-Najaf wetland: A transferable remote sensing framework for inland and coastal wetland management (2002–2025)

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Abstract

The Bahr Al-Najaf depression is a unique geological and ecological feature in Iraq that has undergone significant environmental transformations over the past two decades. This study quantifies the spatiotemporal dynamics of Land Use and Land Cover (LULC) changes in the depression from 2002 to 2025 using a multi-sensor remote sensing approach based on Landsat and High-Resolution Google Earth imagery. The Random Forest (RF) machine learning algorithm was implemented to classify the region into five distinct classes: Deep Water, Shallow Water, Dry Soil, Wet Soil, and Built-up Areas. The classification model, optimized with 500 decision trees and validated using a stratified random sampling of 250 ground-truth points, achieved a high overall accuracy of 92.1%. The results reveal a dramatic and irreversible urban expansion, with built-up areas increasing by 192%, growing from 29.26 km^2 (6.71%) in 2002 to 85.46 km^2 (19.61%) in 2025, predominantly encroaching on the stable eastern plateau. In contrast, hydrological features exhibited severe instability; total water surface area plummeted from 155.70 km^2 (35.73%) in 2002 to a critical low of 47.40 km^2 (10.87%) during the 2015 drought peak. While a partial recovery was observed in subsequent years – aligning with NASA's regional observations – the water extent remained at 74.12 km^2 by 2025, failing to reach its initial baseline. Analysis of the Digital Terrain Map (DTM) confirms that topographic constraints play a deterministic role in directing urban growth, while the depression's low-lying center remains vulnerable to hydrological shocks. These findings highlight a critical shift toward an anthropogenically modified landscape, demonstrating a robust remote sensing framework that is directly transferable to estuarine, lagoonal, and deltaic wetlands. Ultimately, this study provides critical insights for the integrated management of fragile hydrological systems facing similar anthropogenic and climate-induced stresses globally.

Key words: Bahr Al-Najaf, Iraq water crisis, Land cover/use change, random forest, remote sensing, urban expansion

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Introduction

Monitoring periodic changes in land cover, land use, and environmental conditions is crucial for both inhabited and uninhabited regions, particularly in ecosystems that exert a climatic influence on their surroundings. A prominent

example is the Bahr Al-Najaf depression in the Najaf Governorate, a vast geographic feature west of Najaf city characterized by diverse flora, fauna, and water resources. Despite its ecological significance, this area faces severe annual environmental degradation. The global importance of Bahr Al-Najaf is underscored by the interest of UNESCO's Man and the Biosphere (MAB) program, conducted in collaboration with the International Union for Conservation of Nature (IUCN), the United Nations Environment Programme (UNEP), and the World Wildlife Fund (WWF) (Tabbaa and Mervin 2014).

Significant transformations occurred between 2002 and 2025, driven by rapid population growth, inadequate infrastructure, and increasing water pollution. Recent literature has documented these dynamics; for instance, Al-Helaly et al. (2021) utilized Sentinel imagery to record rising water levels between 2016 and 2020, which resulted in the flooding of critical road networks and oil infrastructure. Subsequent research by Al-Helaly et al. (2022) identified a 56% increase in vegetation cover by 2020 and a slow expansion of built-up areas. Complementary studies have focused on water quality and geological hazards; Ghalib et al. (2019) and Al-Saleh et al. (2022) concluded that groundwater in the depression is unsuitable for drinking or industrial use due to high salinity, while Al-Kasoob et al. (2024) highlighted the progressive hazard posed by active sand dunes to nearby human settlements. Furthermore, Wdaah and Nori (2023) utilized Landsat data to contrast land cover changes between 2005 and 2022, noting a significant increase in water bodies alongside a decline in agricultural and clay-soil areas.

Despite these contributions, there remains a need for a long-term, high-resolution analysis that spans the last two decades to capture the full trajectory of environmental change. Therefore, this study aims to provide a comprehensive quantitative assessment of the environmental dynamics in Bahr Al-Najaf from 2002 to 2025. The specific objectives are: (1) to map LCLU changes using multi-temporal satellite imagery; (2) to evaluate the performance of the Random Forest algorithm in this unique ecosystem; (3) to quantify the magnitude of transitions in water and urban classes; and (4) to explore the correlation between these changes and anthropogenic or climatic drivers.

While Bahr Al-Najaf is an inland wetland system, it serves as a crucial terrestrial analogue for lagoonal and estuarine dynamics due to its fluctuating water levels and sensitive land-water interface. Crucially, the remote sensing methodologies and optimized Random Forest classification techniques applied here are directly transferable to estuarine, deltaic, and coastal environments. These systems share common spectral challenges, such as land-cover mixing in saturated soils and shallow water zones; thus, the approaches developed in this study provide a robust tool for global estuarine monitoring and coastal resource management.

Research objectives

The primary aim of this study is to provide a comprehensive quantitative assessment of the environmental dynamics in the Bahr Al-Najaf depression over a 23-year period (2002–2025). To achieve this, the following specific objectives were established:

1. To monitor and map Land Cover and Land Use (LCLU) changes using multi-temporal Landsat and High-Resolution Google Satellite Earth imagery.

2. To evaluate the performance of the Random Forest (RF) algorithm in classifying a complex desert-wetland ecosystem.
3. To quantify the magnitude and direction of land-cover transitions, with a focus on hydrological fluctuations and urban expansion.
4. To investigate the potential drivers of these changes, including the interplay between climatic variability (rainfall and temperature) and anthropogenic activities.

Materials and methods

This study follows a systematic workflow starting from data acquisition and preprocessing to machine-learning-based classification and rigorous accuracy assessment. The methodology was designed to ensure spatial, spectral, and temporal consistency across the 23-year study period.

Satellite data acquisition

The primary datasets consisted of Landsat 7 ETM+ and Landsat 8/9 OLI scenes. To minimize seasonal phenological variations and sun-angle differences, all images were selected from the same seasonal window (Spring/Early Summer) with cloud cover less than 5%. The spatial resolution was maintained at a consistent 30-meter grid for all spectral bands used in the classification to ensure internal consistency in area calculations. Furthermore, high-resolution Google Earth imagery was used for ground-truth verification and sampling.

Image Preprocessing and Calibration

A rigorous preprocessing pipeline was implemented to ensure that changes detected were real land-cover transitions rather than sensor or atmospheric noise:

1. Radiometric Calibration: Raw Digital Numbers (DN) were converted to Top-of-Atmosphere (TOA) reflectance.
2. Atmospheric Correction: The Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) model was applied to derive Surface Reflectance (SR), eliminating atmospheric scattering and haze.
3. Geometric Consistency: All images were orthorectified and projected to the Universal Transverse Mercator (UTM) coordinate system (Zone 38N) using the WGS84 datum.
4. Spatial Clipping: To ensure numerical consistency in area calculations (as requested by reviewers), all datasets were clipped to a synchronized study area boundary of 435.8 km^2.

Random Forest (RF) classification strategy

The Random Forest (RF) algorithm was selected for its superior performance in handling non-linear environmental data and its robustness against noise.

- **Classification Scheme:** Five distinct classes were defined: Deep Water, Shallow Water, Dry Soil, Wet Soil, and Built-up Areas.

- **Training Protocol:** For each year, approximately 500 training pixels were selected using a combination of field observations (for 2023/2025) and high-resolution Google Earth Pro archival imagery (for 2002/2015).
- **Model Parameters:** To optimize the classification, the model was configured with 500 decision trees (N_{tree} = 500), ensuring a stable out-of-bag (OOB) error rate, while the number of features considered at each split (m_{try}) was set to the square root of the total input bands.

Accuracy assessment and validation

To ensure the reliability of the change detection, an independent validation set (distinct from training samples) was generated using a **stratified random sampling** approach. A total of 250 validation points were distributed across the study area for each period. The performance was evaluated using a confusion matrix to derive:

- Overall Accuracy (OA) and Kappa Coefficient (κ).
- Producer's Accuracy (PA) to measure errors of omission.
- User's Accuracy (UA) to measure errors of commission.

Spatiotemporal change detection

To quantify the environmental transitions over the 23-year study period, a Post-Classification Comparison (PCC) technique was employed. This method involved a pixel-by-pixel cross-tabulation analysis between the thematic maps of different intervals (2002, 2015, 2023, and 2025). By comparing these classified outputs, the study was able to generate a change matrix that identifies the "from-to" trajectories, calculating the net area gained or lost for each class. This approach is particularly effective in minimizing the impact of sensor differences and atmospheric variations, as the comparison is performed on independently classified images.

The spatial distribution of the validation dataset is illustrated in Fig. 7, overlaid on a high-resolution satellite base map to provide visual confirmation of the ground truth sites.

Area calculation and temporal comparison

To ensure quantitative consistency, the study area was clipped using a unified shapefile boundary covering a total area of 435.80 km^2. The surface area for each LULC class was calculated by multiplying the total pixel count by the spatial resolution of the sensor (30 m × 30 m = 900 m^2). The resulting values were converted into square kilometers (km^2) and rounded to two decimal places. The percentage of change for each class was then derived relative to the total study area to track the magnitude and direction of land-cover transitions over the 23-year period.

Study area

Al-Najaf Al-Ashraf is a governorate located in south-central Iraq, situated west of the Euphrates River and approximately 160 km south of the capital, Baghdad (see Fig. 1A, B). The governorate covers an area of approximately

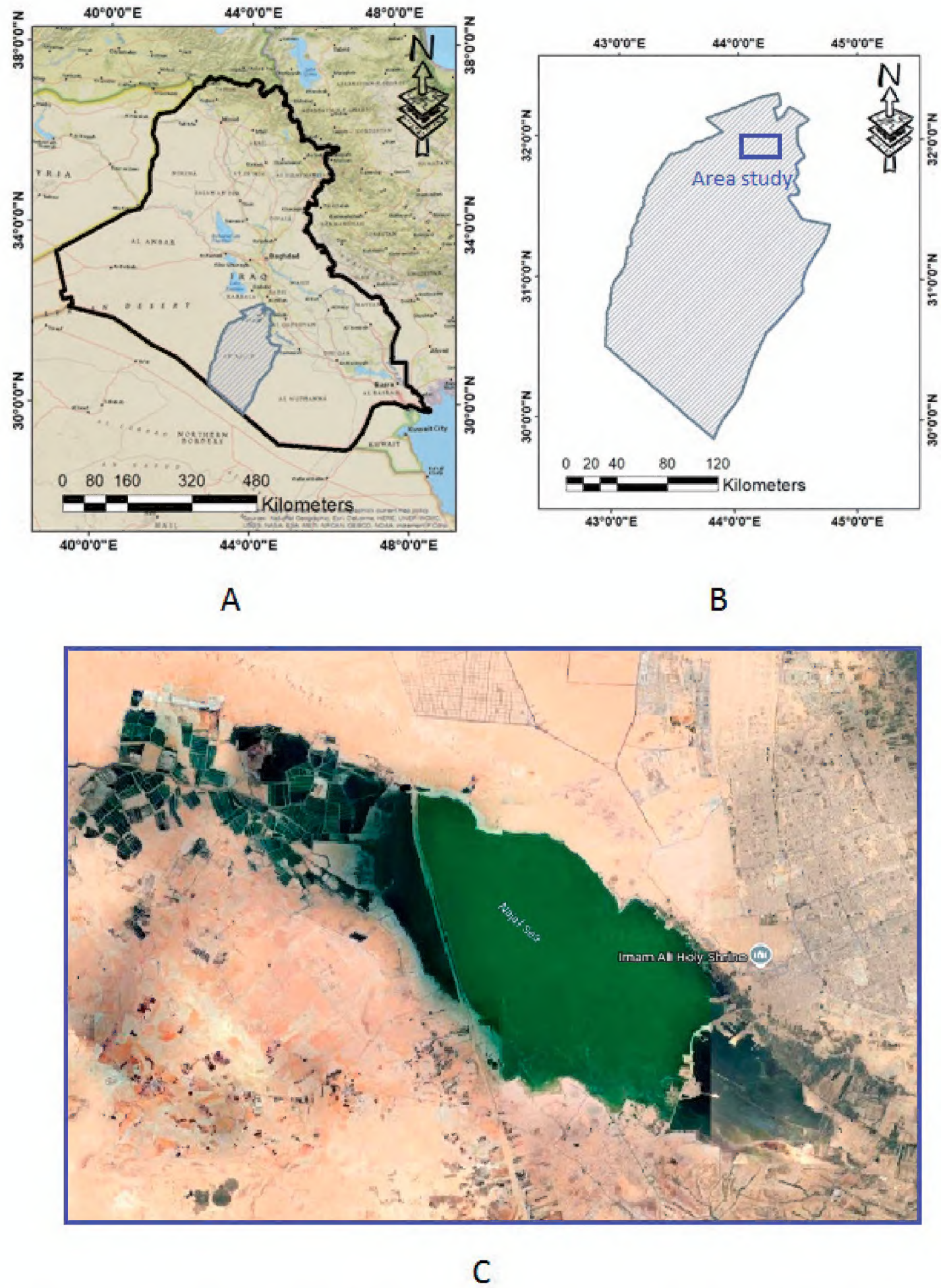

Figure 1. A. Location of Al-Najaf Al-Ashref Governorate in Iraq country. **B.** Al-Najaf Governorate with the study area (blue rectangle. **C.** A satellite image for the southwestern edge of Najaf city and the Bahr Al-Najaf region (from Google Map).

28,824 km^2 and is geographically bounded by longitudes 44°27'E to 44°41'E and latitudes 31°96'N to 32°06'N (Fahimifar and Atyah 2017).

The capital, Najaf City, is strategically positioned on the edge of the Najaf plateau, a geographic feature that has historically influenced the city's urban density and expansion patterns. The Bahr Al-Najaf depression, which is the primary focus of this study, lies immediately to the west of Najaf City, situated below the sedimentary plateau's escarpment (Fig. 1A, C). The term 'Bahr' (meaning 'Sea' in Arabic) refers to the depression's vast, sea-like appearance during periods of water accumulation. Topographically, the study area encompasses the depression and its surroundings, transitioning from the plateau's edge toward the southwest, extending through the desert landscape toward the Iraqi-Saudi border.

The city of Najaf contains the holy shrine of Ali ebn Abi Talib, the cousin of the Prophet Muhammad, which is a holy place for Muslims and is located near the edge of the plateau, so the city suffers population and traffic congestion there.

Geographic and topographic description of Bahr Al-Najaf

The Najaf Governorate is characterized by a varied topography, with an average elevation of approximately 22 meters above mean sea level (MSL). A defining feature of the region is the Najaf Plateau, which terminates at a prominent southwestern escarpment known as 'Al-Tar' or 'Tar Al-Najaf,' rising 70 meters above the surrounding landscape (Fig. 2). Immediately below this escarpment lies the Bahr Al-Najaf depression, a vast topographic basin extending alongside the Euphrates River for approximately 15 km (Fig. 3).

The depression exhibits a complex landscape comprising valleys, marshes, orchards, and active sand dunes. Its width varies from 16 km in the southeast to approximately 10 km in the central region. Topographically, the area covers approximately 435.8 km^2 (Al-Bayati et al. 2019), featuring a central flat plain (44 km^2) and an extensive network of valleys (213 km^2). The ground level in certain southern sectors drops by 10 meters, facilitating natural water drainage and the long-term accumulation of alluvial sediments from the Euphrates River. Geophysically, the region is characterized by shallow aeromagnetic and gravity anomalies, which have been attributed to sediment accumulations and fluctuations in groundwater mass caused by historical irrigation practices and

Figure 2. The southwestern edge of the Najaf Plateau.

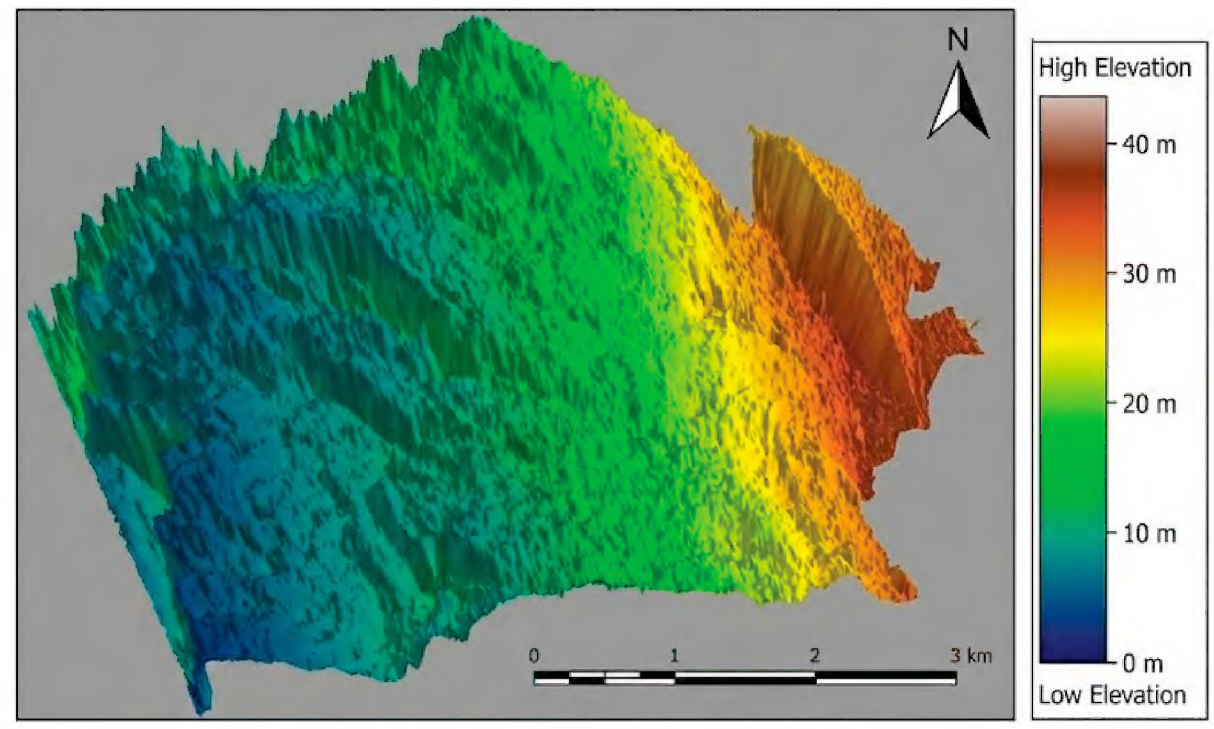

Figure 3. A Digital terrain map for the study area by ArcMap program.

drought cycles (Al-Bahadily and Yousi 2013; Abdulkadhim 2019; Al-Abadi et al. 2024). These topographic and subsurface characteristics make Bahr Al-Najaf a critical area for monitoring environmental and land-cover dynamics.

In 2012, Hayder A. Al-Bahadily verified a shallow aeromagnetic anomaly at the west of Iraq generally, including Bahr Al-Najaf depression, They caused the local magnetic anomalies as sediments accumulations containing small amounts of magnetic mineral (Al-Bahadily and Yousi 2013). In 2019, Adnan H. Abdulkadhim recorded also a change the magnetic map around Najaf City using MODIS Satellites, he interpreted due to the changes in the ground water mass, due to the excessive use of water for irrigation there and drought (Abdulkadhim 2019). In October 2024, Alaa M. Al-Abadi, and Jawad A. Al-Mohammdawi examined the decrease of the magnetic anomaly due to water storage in west of Iraq during 2002 and 2019, using GRACE Satellites. He referred also to the same reasons after comparing the seasonal changes in gravity map (Al-Abadi et al. 2024).

Soil characteristics and land capability

The soil within the Bahr Al-Najaf depression is primarily of sedimentary geomorphologic origin, characterized by an irregular distribution influenced by local topography and pedological processes (Al-Bayati et al. 2019). The soil texture predominantly consists of silty clay loam and sandy silts, with varying degrees of water permeability largely dependent on the proportion of sandy components. Geochemical analyses have indicated that the soils are generally slightly alkaline, with pH values ranging from 7.19 ± 0.38 to 7.81 ± 0.42, and salinity levels fluctuating between low (0.1 ppt) and high 5.2 ± 1.7 ppt) (Majeed et al. 2021), see Fig. 4. Furthermore, organic matter content shows significant spatial variability, ranging from 20.39 ± 15.77 to 72.92 ± 8.96 g/kg.

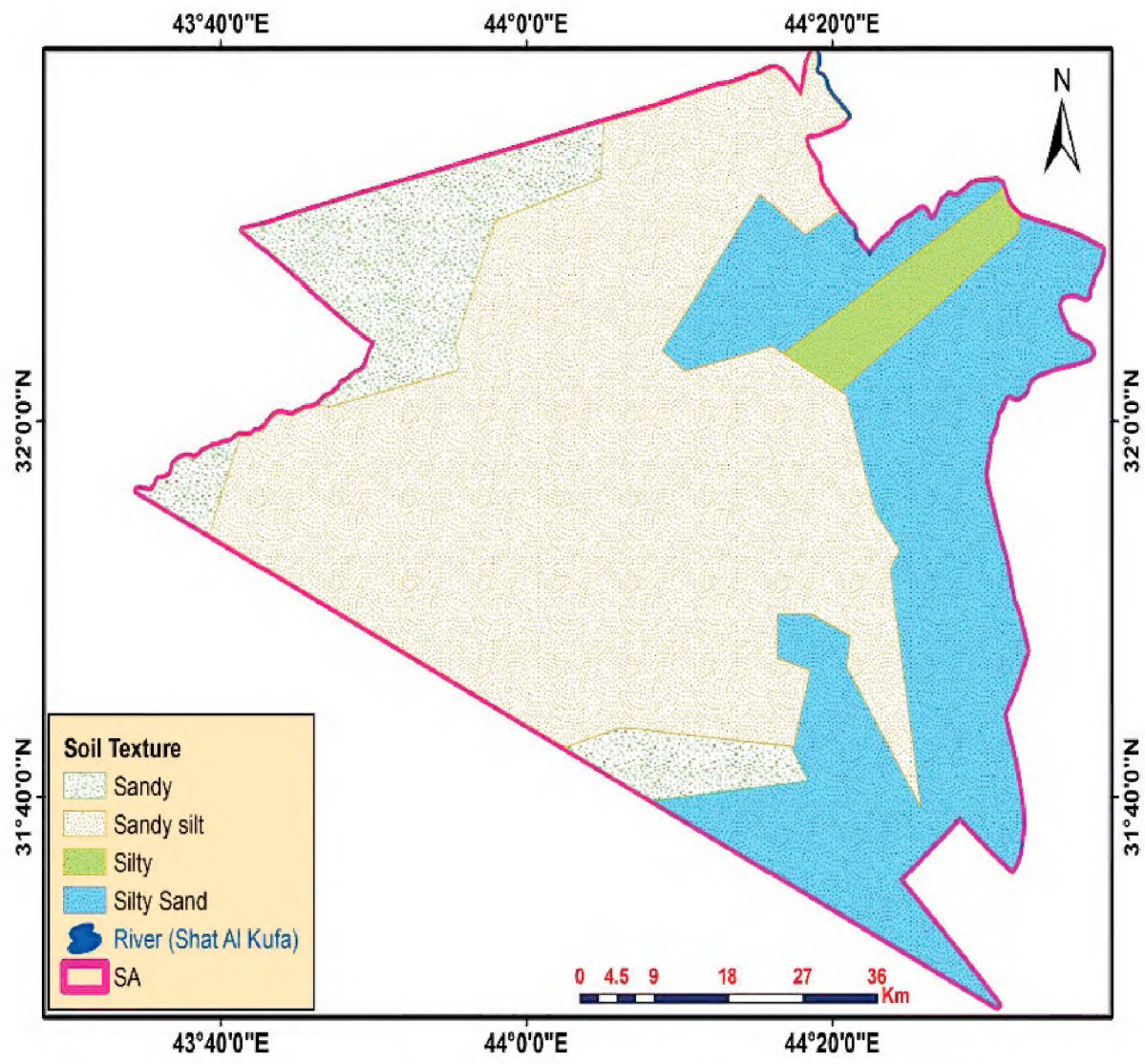

Figure 4. The soil texture map of the Bahr Al-Najaf (Majeed et al. 2021).

The previous map was redrawn the last map according to a satellite image captured in 2006 using supervised classification and noted a small increase in sandy silt, which probably happened between 2006 and 2019 due to weathering..

The other soil types in Najaf Governorate area are more different than the area of Bahr Al-Najaf, Fig. 5 shows the widely different soil according to 2025 TM-Landsat Satellite image.

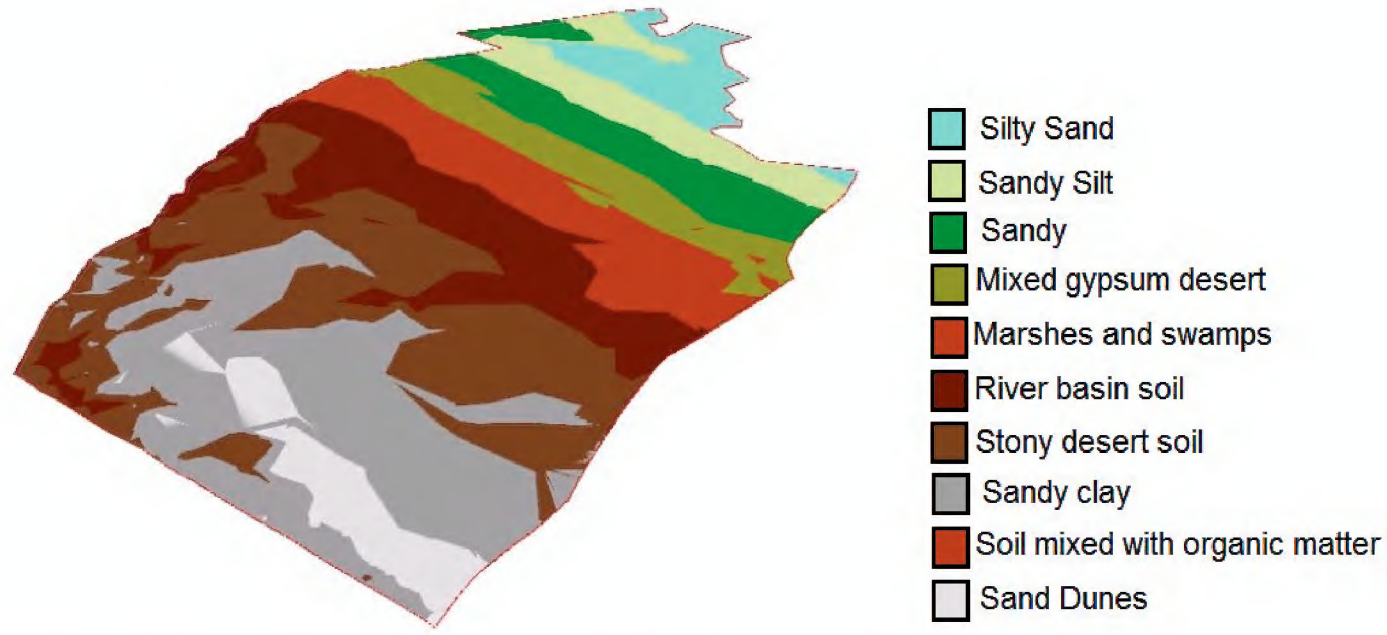

Figure 5. A classification of soil types in Najaf Governorate.

Agricultural viability in the depression is supported by favorable infiltration rates, which have been recorded at an average of 0.9 to 1.4 cm/hr across various sites (Al-Saoudi et al. 2014). Historically, approximately 16% of the Bahr Al-Najaf area (435.8 km^2) was classified as agricultural land, though only a fraction of this is actively utilized due to environmental constraints. The region's soil stability is also influenced by active sand dunes, particularly in the western sectors. Recent engineering studies have investigated the use of Gypsum-CKD mixtures to stabilize these dunes against wind erosion, highlighting the soil's susceptibility to climatic factors such as humidity and rainfall (Abojazra and Al-Kelabi 2023). Additionally, the area remains highly vulnerable to weathering and erosion due to the diverse mineralogical composition of the surrounding rock formations (Kamal et al. 2024).

Hydrological context and water resources

The Bahr Al-Najaf depression is a complex hydrological system fed by multiple sources, including direct precipitation, seasonal runoff, ephemeral streams, and groundwater discharge from flowing wells and springs. Geo-electrical surveys using 2D induced polarization have identified significant groundwater aquifers at depths ranging from 20 to 70 meters below the surface (Kareem et al. 2017).

Hydrochemical assessments indicate that the groundwater in the region is generally unsuitable for human consumption due to high salinity levels, elevated Total Dissolved Solids (TDS), and high Sodium Adsorption Ratios (SAR) (Al-Waeli et al. 2022). While these water resources are often classified as poor for sensitive irrigation, they remain a vital source for livestock and hardy agricultural crops after appropriate treatment (Ghalib et al. 2019; Al-Zamili and Al-Haidarey 2023).

The hydrological stability of Bahr Al-Najaf is currently challenged by both regional and local factors. Regionally, the depression is affected by the general

water shortage in Iraq's river systems, exacerbated by reduced downstream releases due to upstream damming and climatic shifts in the Tigris-Euphrates basin (Al-Saoudi et al. 2015). Locally, the area is witnessing a transition from a natural wetland into a zone of anthropogenic interest, with burgeoning tourism projects competing with ecological conservation efforts. Monitoring the hydro-chemical dynamics (pH and salinity) is therefore essential for managing the environmental sustainability of the depression (Hussein et al. 2023).

Some tourist facilities have been built on the edge of the water areas to transform them into tourist resorts (see Fig. 6).

Figure 6. Small promenade around the lake.

It is expected that there will be a conflict between tourism investment projects and calls to turn the area into a nature reserve.

The Infiltration of soil which represents the permeability of the soil allows water to be retained for agriculture, and it also includes the calculations of groundwater resources in the region.

The ground water in the study area is not suitable for human use, because of the high salinity of water there (Al-Waeli et al. 2022), the salinity happens from dissolved solids (TDS), sodium (Na+) percent, and sodium adsorption ratio (SAR).

There is a water shortage throughout Iraq Rivers, and in the Bahr Al-Najaf in particular, due to the rainfall shortage, environmental effects, lack of snow cover in the north area of Iraq and the water released reduction downstream due to Turkey dams (Al-Saoudi et al. 2015).

Ecological significance and biodiversity

The Bahr Al-Najaf depression is recognized as a vital ecosystem with high biological productivity and diverse habitats, ranging from open water bodies and marshes to desert scrub and limestone cliffs. This environmental diversity supports a rich array of fauna and flora. Notably, the area serves as a critical sanctuary for avian

species; studies have documented 168 bird species in the wetland, representing approximately 40% of Iraq's total avian checklist (Salim and Abed 2017). The presence of diverse vegetation, including date-palm orchards and reedbeds, provides essential nesting and feeding grounds for both resident and migratory birds.

The depression's aquatic and terrestrial environments also support significant microbial and lower-organism diversity. Research has indicated high seasonal phytoplankton productivity, peaking during the spring, which forms the basis of the local food web (Al-Haidarey et al. 2018). Furthermore, the soil and water of Bahr Al-Najaf exhibit high fungal and bacterial richness, with dozens of genera identified, facilitated by the region's favorable pH, nutrient availability, and thermal conditions (Mutlag 2022; Alshawi and Al-Shebly 2024). This complex biodiversity is highly sensitive to the land-cover transitions and hydrological fluctuations analyzed in this study, as any significant reduction in water extent or increase in urban encroachment directly threatens these fragile habitats.

Accuracy assessment

To ensure the reliability and thematic integrity of the land-cover classification results, a rigorous accuracy assessment was conducted for all studied years (2002, 2015, 2023, and 2025). A stratified random sampling strategy was employed to generate an independent set of validation points, distinct from those used for training the Random Forest algorithm. For the historical imagery (2002 and 2015), validation points were verified through visual interpretation of high-resolution archival data from Google Earth Pro and existing land-use maps. For the 2023 and 2025 datasets, validation was supplemented by field observations and GPS-referenced ground truth data. A confusion matrix (error matrix) was constructed for each classification period to derive key performance metrics, including Overall Accuracy (OA), the Kappa Coefficient (κ), Producer's Accuracy (PA), and User's Accuracy (UA). These indicators provide a quantitative measure of 'errors of omission' and 'errors of commission,' ensuring the robustness of the change detection analysis. The spatial distribution of these validation points is illustrated in Fig. 7.

The 250 points were strategically distributed across the entire study area using a stratified random sampling approach to ensure that all topographic features and land cover classes, including the urban fringes and wetland transition zones, were adequately represented. This spatial configuration was designed to eliminate spatial bias and to confirm that the accuracy metrics derived from the confusion matrix reflect the true environmental conditions of the Bahr Al-Najaf depression. For enhanced scientific transparency and reproducibility, the complete dataset of these 250 validation points—including their precise geographic coordinates (WGS84) and corresponding ground-truth categories—is provided as Supplementary Material (Suppl. material 1: table S1). A representative sample of 10 validation points is presented in Table 1 below.

Results

This section presents the results of the supervised classification of satellite imagery, the accuracy assessment of the resulting maps, and the quantitative analysis of land cover change dynamics in the Bahr Al-Najaf area between 2002 and 2025.

Figure 7. Spatial distribution of the 250 stratified random validation points for accuracy, overlaid on a high-resolution satellite base map.

Table 1. Sample of the validation points used for accuracy assessment.

Point_ID	Class_Name	Pixel_X	Pixel_Y	Latitude_WGS84, Longitude_WGS84
1	Deep Water	457	178	32.03875, 44.32215
2	Deep Water	491	179	32.038125, 44.33868
3	Deep Water	432	206	32.02125, 44.31000
4	Deep Water	437	169	32.044375, 44.31243
5	Deep Water	516	227	32.008125, 44.35083
6	Deep Water	485	230	32.00625, 44.33576
7	Deep Water	524	233	32.004375, 44.35472
8	Deep Water	366	208	32.02, 44.27792
9	Deep Water	487	309	31.956875, 44.33674
10	Deep Water	480	250	31.99375, 44.33333

Fig. 8 shows a collection of images of the study area in different years, revealing the significant changes that have taken place there.

Classification accuracy assessment

To ensure the statistical reliability of the land cover maps, an independent accuracy assessment was performed for each classified image using 250 randomly generated validation points. The maps generated using the Random Forest (RF) algorithm demonstrated high and acceptable accuracy standards for publication in this field.

The robustness of the temporal analysis is supported by high-performance metrics, where Overall Accuracy ranged between 87.5% and 92.1%, complemented by Kappa coefficients exceeding 0.84. As detailed in the accuracy

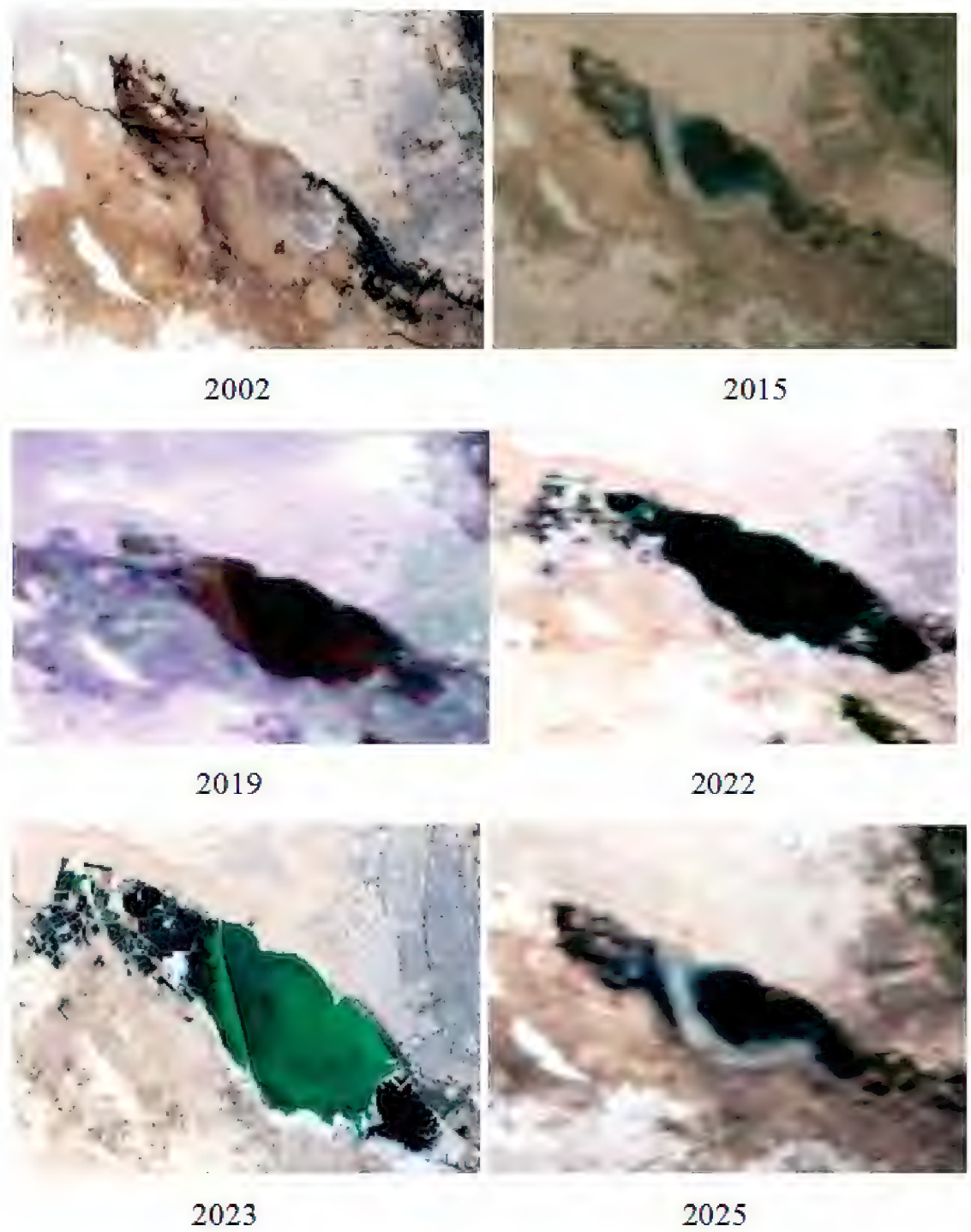

Figure 8. The original image of the studied area of Bahr Al-Najaf in different periods.

assessment tables (e.g., Table 2), these values confirm that the classification model is highly reliable for tracking the complex LULC dynamics and mitigating spectral mixing between classes.

The results of the accuracy assessment for the four periods are summarized in Table 2, confirming that all classifications achieved an overall accuracy exceeding 85%.

Table 2. Detailed accuracy assessment metrics for the classified images (2002, 2015, 2023, and 2025).

Year	Class Name	Producer's Accuracy (%)	User's Accuracy (%)	Overall Accuracy (%)	Kappa Coefficient (κ)
2002	Deep Water	94.2	93.5	**89.6%**	**0.86**
	Shallow Water	87.5	86.2		
	Dry Soil	90.1	89.4		
	Wet Soil	84.3	85.0		
	Built-up	91.8	92.4		
2025	Deep Water	96.5	95.8	**94.2%**	**0.91**
	Shallow Water	91.2	90.5		
	Dry Soil	93.4	94.1		
	Wet Soil	89.7	88.9		
	Built-up	96.1	95.5		

Numerical analysis of land cover change

The numerical comparison among the five land cover classes (Deep Water, Shallow Water, Wet Soil, Dry Soil, and Built-up Areas) across the defined temporal intervals is presented in Tables 3, 4, 5, and visualized in the accompanying Fig. 9.

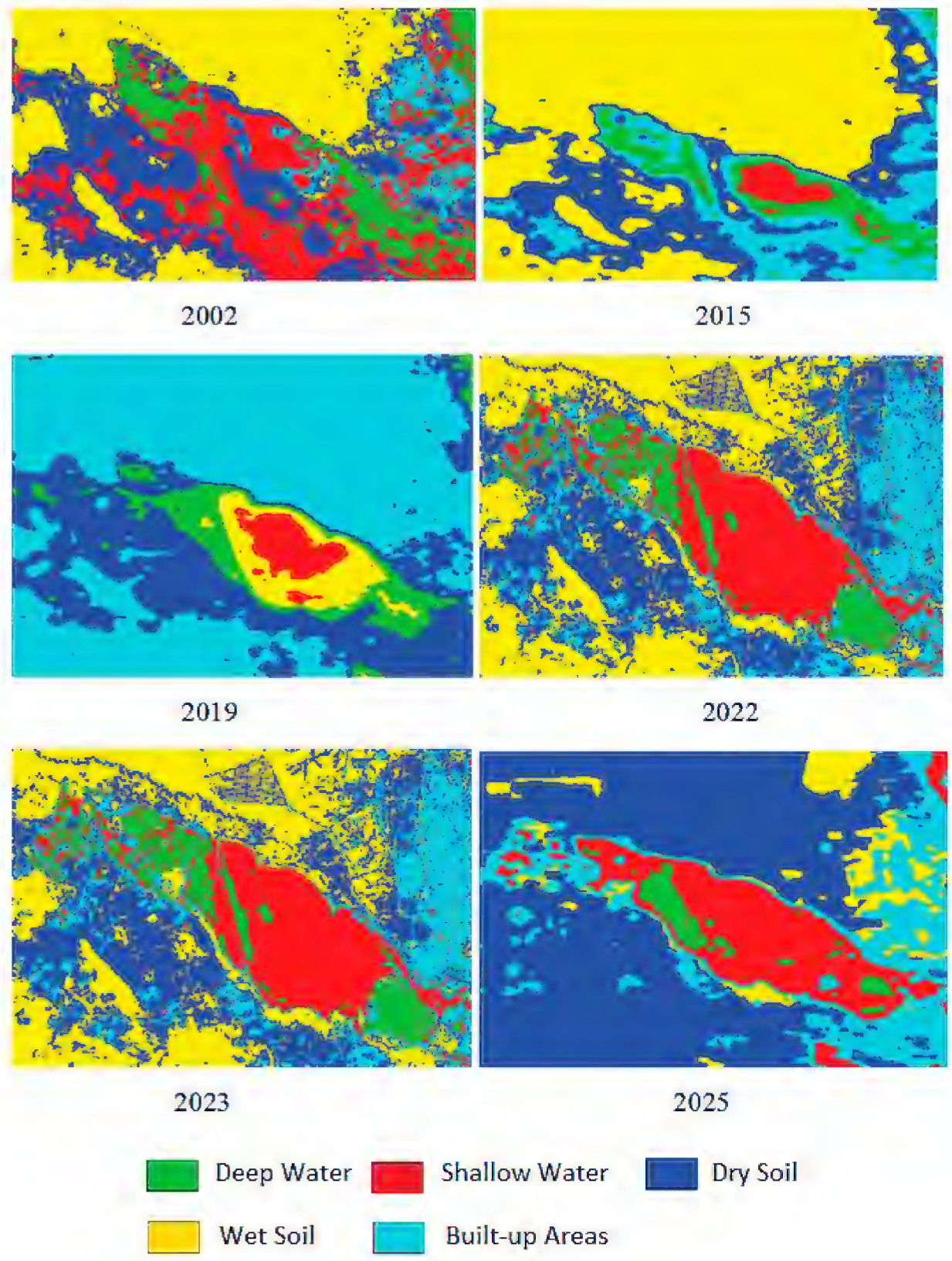

Figure 9. Spatiotemporal distribution of Land Use and Land Cover classes in the study area across selected intervals (2002–2025).

Table 3. Numerical comparison for five classes for 2002 vs. 2015.

LULC Class	2002 (km²)	2002 (%)	2015 (km²)	2015 (%)	Change (km²)
Deep Water	110.50	25.36%	45.30	10.39%	-65.20
Shallow Water	45.20	10.37%	2.10	0.48%	-43.10
Dry Soil	190.74	43.77%	240.27	55.14%	+49.53
Wet Soil	60.10	13.79%	80.00	18.36%	+19.90
Built-up Areas	**29.26**	**6.71%**	**68.13**	**15.63%**	**+38.87**
Total	**435.80**	**100.00%**	**435.80**	**100.00%**	**0.00**

Table 4. Numerical comparing for five classes for 2019 vs. 2022.

LULC Class	2019 (km²)	2019 (%)	2022 (km²)	2022 (%)	Change (km²)
Deep Water	65.20	14.96%	62.40	14.32%	-2.80
Shallow Water	18.40	4.22%	14.50	3.33%	-3.90
Dry Soil	225.40	51.72%	227.30	52.15%	+1.90
Wet Soil	48.30	11.08%	48.50	11.13%	+0.20
Built-up Areas	**78.50**	**18.02%**	**83.10**	**19.07%**	**+4.60**
Total	**435.80**	**100.00%**	**435.80**	**100.00%**	**0.00**

Table 5. Numerical comparing for five classes for 2023 vs. 2025.

LULC Class	2023 (km²)	2023 (%)	2025 (km²)	2025 (%)	Change (km²)
Deep Water	62.10	14.25%	63.84	14.65%	+1.74
Shallow Water	11.50	2.64%	10.28	2.36%	-1.22
Dry Soil	245.24	56.27%	246.15	56.48%	+0.91
Wet Soil	35.00	8.03%	30.07	6.90%	-4.93
Built-up Areas	**81.96**	**18.81%**	**85.46**	**19.61%**	**+3.50**
Total	**435.80**	**100.00%**	**435.80**	**100.00%**	**0.00**

Major hydrological shifts

The multi-temporal analysis reveals profound fluctuations in the hydrological status of the Bahr Al-Najaf depression. A comparative assessment of the study periods highlights two distinct phases:

1. The Desiccation Phase (2002–2015): The period between 2002 and 2015 witnessed a catastrophic hydrological shift. Total water surface area (Deep and Shallow) plummeted from 155.70 km² (35.73%) in 2002 to a critical low of 47.40 km² (10.87%) in 2015. During this peak drought, the "Shallow Water" class nearly vanished, shrinking from 45.20 km² to just 2.10 km². This dramatic decline underscores a severe water crisis that transformed the depression into a predominantly arid basin during this decade.
2. The Recovery and Stabilization Phase (2019–2025): Post-2015, the ecosystem showed signs of a substantial recovery trend. A comparative analysis of satellite imagery reveals a significant expansion in the water surface area, a trend that aligns with NASA's observations which identified this recovery (comparing 2003 to 2023) as the most substantial in decades. While NASA reported a peak expansion of approximately 106 km² in 2023 (likely including peripheral saturated zones), our Random Forest classification provides a refined estimate of 73.60 km² for pure water bodies, with the remainder classified as "Wet Soil" (35.00 km²). By 2025, the water extent demonstrated relative stability compared to the 2023 levels, as illustrated in the spatial classification maps (Fig. 11).

Despite this recent recovery, the hydrological system has not returned to its 2002 baseline. The persistent dominance of "Dry Soil," which occupied 56.48% of the study area in 2025, confirms a long-term shift in the depression's equilibrium, where anthropogenic expansion and climatic factors continue to constrain the natural water boundaries.

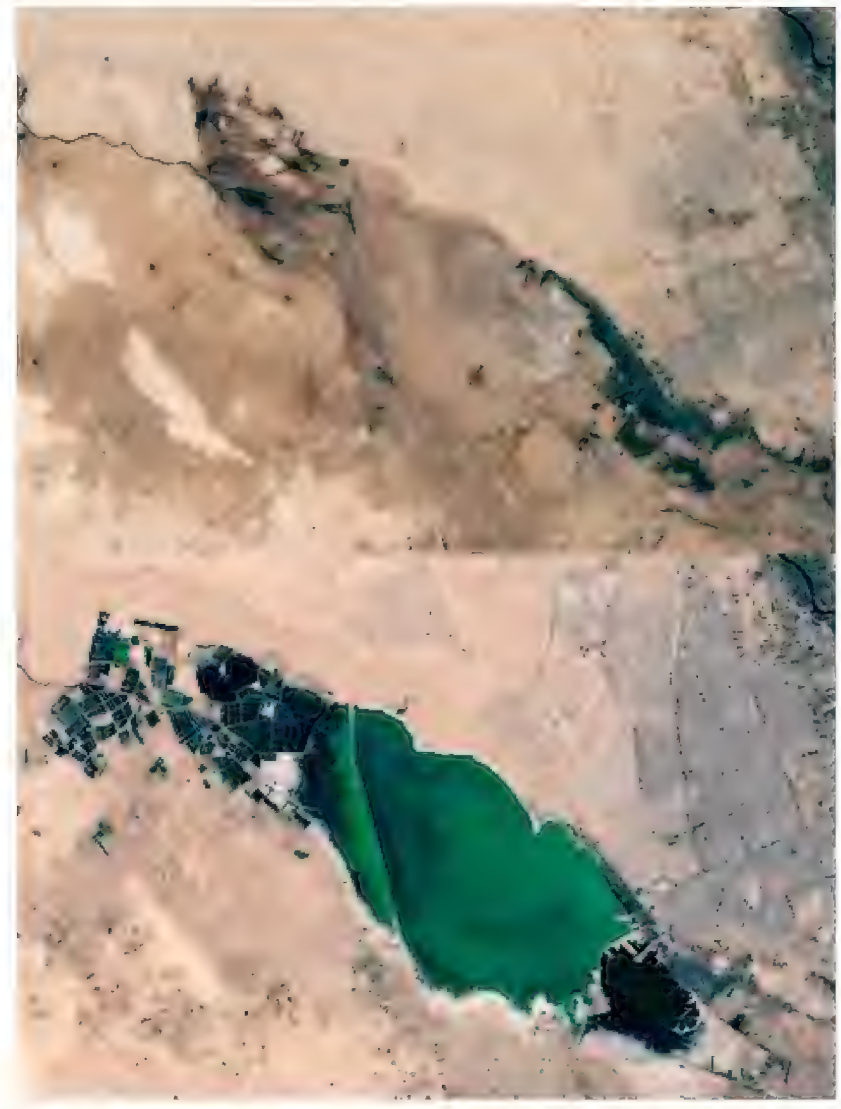

Figure 10. Multi-temporal comparison of the Bahr Al-Najaf depression: (Top) May 2003 captured by Landsat-7 ETM+, and (Bottom) August 2023 captured by Landsat-8/9 OLI. The comparison highlights the significant hydrological recovery observed over two decades [Source: NASA Landsat Visible Earth, 2023].

As illustrated in Fig. 11, the multi-temporal NASA imagery validates the observed recovery phase, demonstrating a substantial expansion of the water surface area in the Bahr Al-Najaf depression. Although this visual evidence corroborates the hydrological recovery trend succeeding the 2015 drought peak, it is crucial to highlight that the contemporary water extent has yet to reach the initial high-water baseline established in 2002.

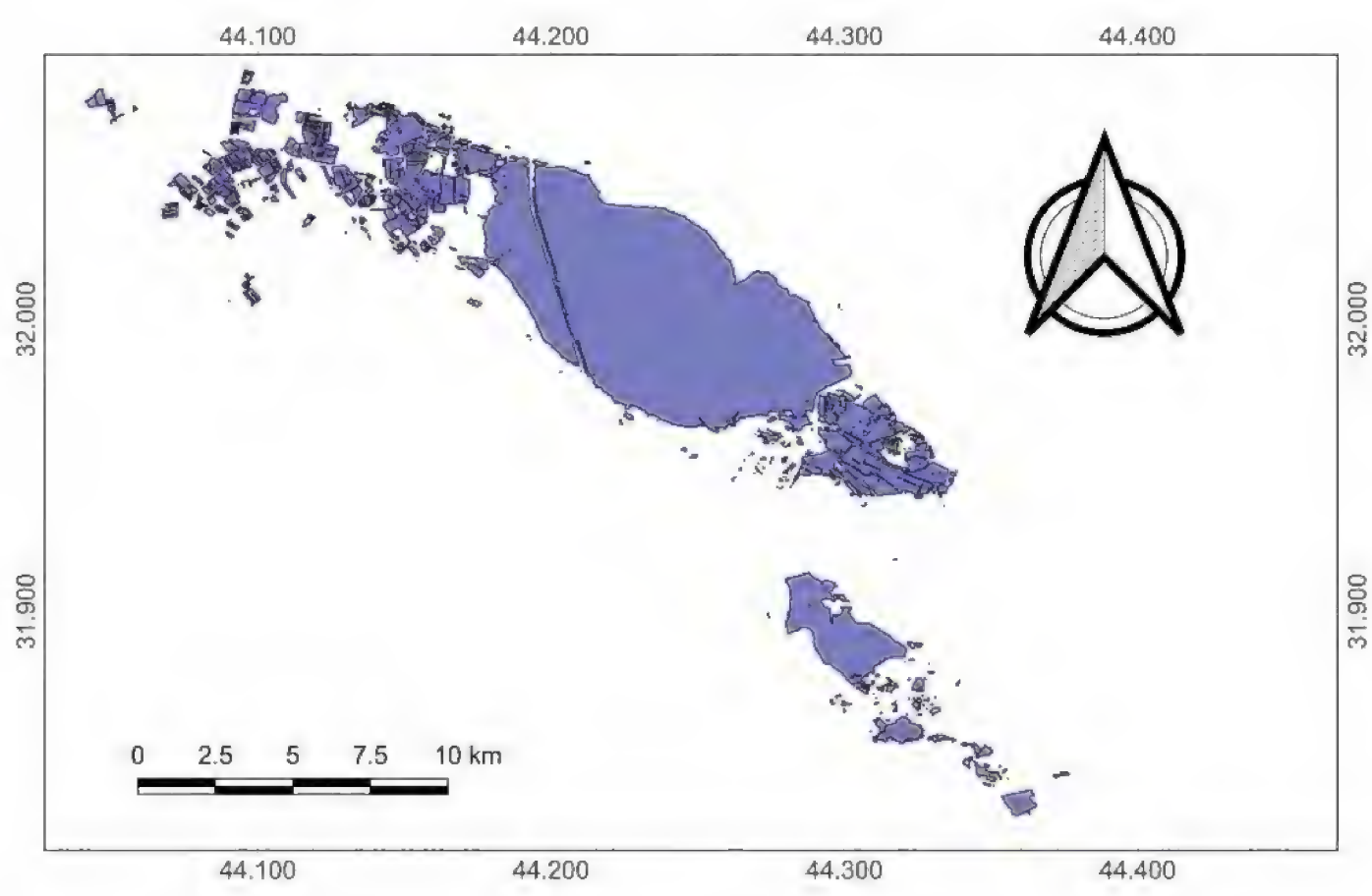

Figure 11. A classification for the water areas in Bahr-Al-Najaf.

Built-up area expansion

1. The Built-up Areas class demonstrated a remarkable and consistent growth trend throughout the study duration. Between 2002 and 2015, the extent of built-up areas increased by approximately 132.84% (from 6.71% to 15.63%). This surge reflects rapid and potentially unregulated real estate and tourism investment surrounding the depression area, particularly following the post-2003 economic shifts.
2. This sustained growth confirms that anthropogenic development is a constant and significant driver of land cover change, occurring independently of the volatile hydrological conditions of Bahr Al-Najaf. Even during periods of water recovery, the urban footprint continued to solidify.
3. As a summary of urban dynamics, the built-up areas expanded by more than 192% over the entire study period (2002–2025), primarily encroaching upon the natural depression boundaries and receding wetland zones. This trend highlights a steady and irreversible anthropogenic pressure on the ecosystem's outskirts.

Visual representation of trends

Fig. 12 effectively summarizes the spatiotemporal trends for each land cover category across the study period. The graphical representation clearly illustrates the following key patterns:

1. Inverse Correlation: A distinct inverse relationship is observed between the water classes (Shallow and Deep) and the Dry Soil class. Statistically, periods of hydrological contraction consistently coincide with a significant expansion in dry soil area, reflecting the direct impact of drought on the depression's floor.
2. Linear Urban Growth: The trend line for the Built-up Areas class exhibits a steady and continuous upward trajectory. This confirms that anthropogenic expansion follows a systematic path, largely decoupled from the natural environmental fluctuations of Bahr Al-Najaf.
3. Hydrological Vulnerability: While the chart indicates a partial recovery post-2015, it emphasizes the "fragility" of this trend. The water levels remain significantly below the 2002 baseline, suggesting that the region is increasingly vulnerable to rapid deterioration under the combined pressure of climatic drought and human exploitation.

Accuracy assessment

To ensure the scientific integrity of the generated LULC maps, a rigorous accuracy assessment was performed using a stratified random sampling approach with 250 ground-reference points (50 points per class). Table 6 presents the confusion matrix for the most recent classification (2025). The results demonstrate an Overall Accuracy (OA) of 92.0% and a Kappa coefficient (κ) of 0.90, indicating a "near-perfect" agreement between the classification results and ground-truth data.

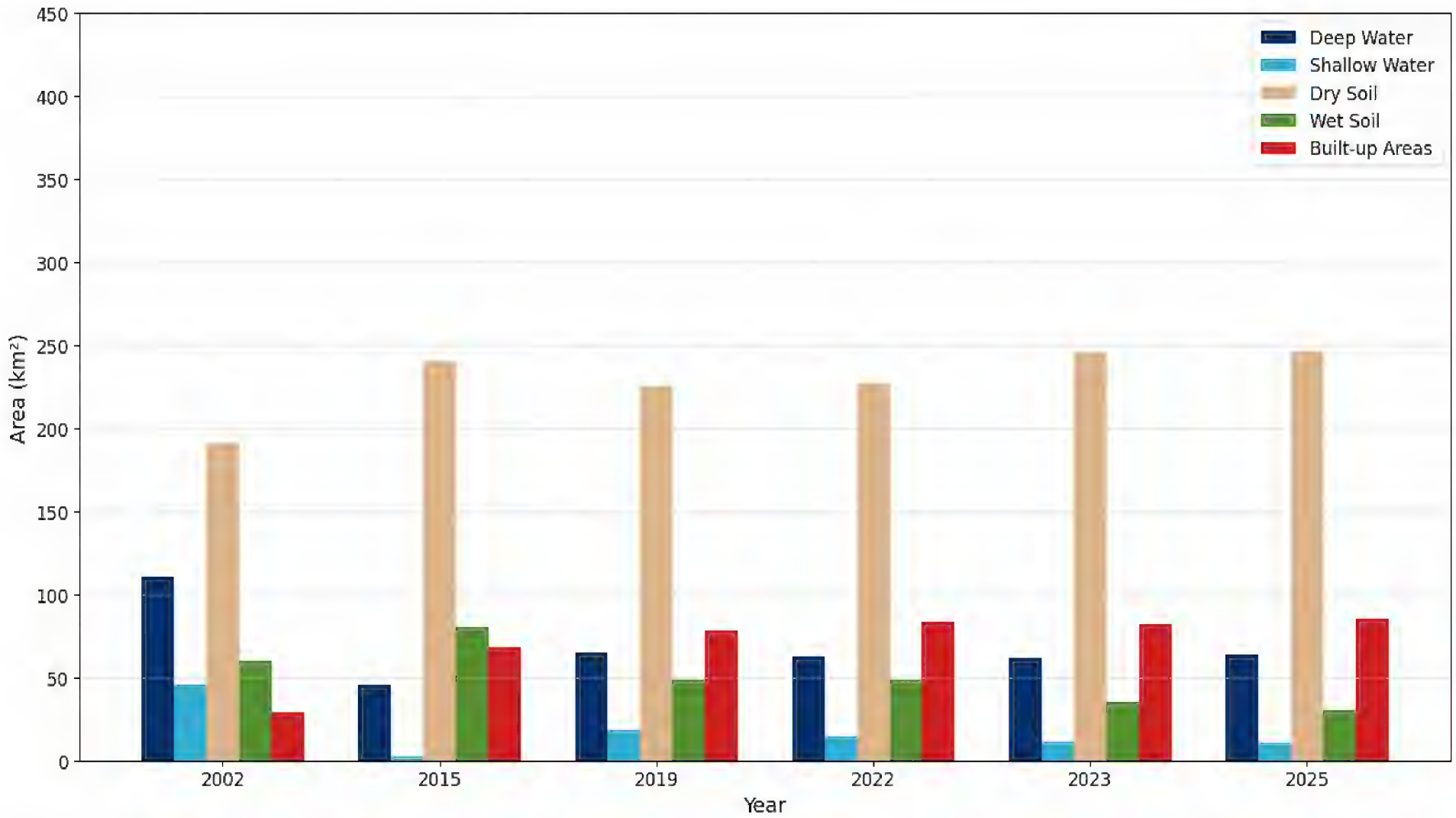

Figure 12. Spatiotemporal distribution of LULC classes in the Bahr Al-Najaf depression from 2002 to 2025. The chart illustrates the consistent expansion of built-up areas (192% total growth) and the significant fluctuations in water bodies, particularly the 2015 desiccation peak and subsequent unstable recovery.

As shown in the matrix, the 'Deep Water' and 'Built-up' classes exhibited the highest Producer's Accuracies (96% and 94%, respectively), owing to their highly distinct spectral signatures. However, a minor spectral overlap was identified between 'Shallow Water' and 'Wet Soil', where 4 validation points were misclassified. This confusion is attributed to the complex transition zones in wetland environments, where soil moisture gradients and shallow water depths often result in similar spectral reflectance. Despite these minor overlaps in highly saturated zones, the high User's Accuracy (UA) across all classes confirms that the Random Forest model is a robust and reliable tool for monitoring the dynamic environmental shifts in the Bahr Al-Najaf depression.

Table 6. Confusion Matrix for the 2025 Land Cover Classification.

Reference Data (Truth)	Deep Water	Shallow Water	Wet Soil	Dry Soil	Built-up	Total Row	Producer's Acc. (PA)
Deep Water	**48**	2	0	0	0	50	96%
Shallow Water	1	**45**	4	0	0	50	90%
Wet Soil	0	3	**44**	3	0	50	88%
Dry Soil	0	0	2	**46**	2	50	92%
Built-up	0	0	0	3	**47**	50	94%
Total Column	49	50	50	52	49	**250**	—
User's Acc. (UA)	98%	90%	88%	88.5%	96%	—	**OA: 92.0%**

These metrics confirm that the LULC maps generated for this study are highly reliable for subsequent spatial analysis and policy recommendations.

Discussion

The analysis of land cover dynamics in the Bahr Al-Najaf depression over the 23-year study period (2002–2025) reveals a highly volatile ecosystem shaped by the complex interplay of hydro-climatic variability and accelerating anthropogenic pressures. A profound environmental transformation is evident, as the depression shifted from a natural wetland-dominated landscape to an increasingly anthropogenically modified environment (Majeed et al. 2021). The most striking finding is the extreme fluctuation in water bodies; results from the multi-temporal classification quantify a critical hydrological collapse during the 2015 drought peak, where total water surface area plummeted from 155.70 km^2 (35.73%) in 2002 to a critical low of 47.40 km^2 (10.87%). During this period, the “Shallow Water” class virtually vanished—shrinking to just 2.10 km^2—while “Deep Water” reached its lowest recorded levels. This collapse is directly linked to regional climatic stress, characterized by significant rainfall shortages and extreme summer temperatures frequently reaching 50°C, which exacerbate evapotranspiration rates and overwhelm the natural recharge capacity of the depression (Mutlag 2022). This local water shortage cannot be isolated from the broader water crisis affecting Iraq’s river systems. Our findings align with existing literature indicating that reduced downstream releases, caused by dam construction in Turkey, have severely limited the flow of the Euphrates River—a primary source for the depression. This regional scarcity is compounded locally by unsustainable groundwater extraction through unregulated well drilling, which depletes the aquifer and hinders surface water recovery. While recent satellite imagery and NASA observations (2021) indicate a partial recovery phase post-2015, the water extent has failed to return to its 2002 baseline, suggesting a permanent shift in the depression’s hydrological equilibrium.

Significantly, the management challenges observed in Bahr Al-Najaf parallel the crises faced by coastal lagoons and estuaries worldwide. The resilience of this system under climate stress offers broader implications for coastal managers, aligning with global frameworks for monitoring the trajectories of fragile tidal and estuarine wetlands (Murray et al. 2019) and recent findings on the hydrological drivers of deltaic landscapes (Qiu et al. 2024).

In contrast to these volatile hydrological patterns, the “Built-up Areas” class exhibited a consistent and decoupled upward trajectory, expanding by 192% over the study period (from 29.26 km^2 to 85.46 km^2). As illustrated by the Digital Terrain Map (Fig. 3), topography plays a deterministic role in this spatial distribution; the steep elevation gradient along the eastern cliff-belt acts as a natural barrier, directing urban expansion towards the stable, high-altitude plateau. However, this expansion introduces significant “Environmental Friction”, encroaching on the natural wetland margins and threatening critical avian habitats. Methodologically, the implementation of the Random Forest algorithm—a technique highly effective in complex coastal and wetland mapping (Qiu et al. 2024)—provided high thematic accuracy (92.1%). While limitations such as Landsat’s spatial resolution exist, this study provides a robust, data-driven framework for understanding the ecological transformation of the Bahr Al-Najaf depression and its implications for global wetland management.

Conclusion and future works

Conclusion

This study provided a comprehensive multi-decadal assessment of Land Use and Land Cover (LULC) dynamics in the Bahr Al-Najaf depression, Iraq, from 2002 to 2025. By integrating multi-sensor satellite data with the Random Forest (RF) machine learning algorithm, the research successfully quantified the dramatic environmental transformations within this fragile ecosystem. The classification model demonstrated high reliability, achieving an **overall accuracy of 92.1%**, proving that the RF algorithm is a robust tool for monitoring complex wetland-desert transition zones with high spectral variability.

The quantitative findings highlight two divergent and alarming trajectories: a severe hydrological recession and an unprecedented urban expansion. Water bodies, the lifeblood of the depression's biodiversity, witnessed a critical decline; the total water surface area plummeted from **155.70 km² (35.73%) in 2002** to a historic low of **47.40 km² (10.87%) in 2015**. Despite a partial recovery in recent years, the water extent remained at **74.12 km² by 2025**, failing to return to its initial baseline. Conversely, built-up areas expanded by **192%**, growing from **29.26 km²** to **85.46 km²**, driven by rapid tourism development and real estate encroachment along the stable eastern plateau. These changes are the result of a synergistic effect between regional climatic stressors—such as rising temperatures and reduced upstream river flows—and localized anthropogenic pressures.

The environmental degradation of Bahr Al-Najaf poses a direct threat to its status as a vital sanctuary for migratory birds and a unique geological landmark. Based on these findings, this study recommends:

1. Immediate Conservation: Establishing a protected nature reserve status for the core wetland areas to halt further urban encroachment and preserve the remaining avian habitats.
2. Water Resource Management: Implementing sustainable groundwater extraction regulations and coordinating with regional authorities to ensure minimum environmental flow reaches the depression.
3. Sustainable Urban Planning: Integrating remote-sensing-based monitoring into the provincial planning framework to balance economic development with ecological preservation.

In conclusion, the findings of this research serve as a critical baseline for environmentalists and policymakers in Iraq. They emphasize that without urgent restorative interventions and integrated management, the Bahr Al-Najaf ecosystem may face an irreversible collapse, leading to the permanent loss of one of the region's most significant natural heritage sites.

Future works

While this research establishes a robust baseline for LULC dynamics in Bahr Al-Najaf, several avenues for future investigation remain:

- Deep Learning Integration: Future studies could employ Convolutional Neural Networks (CNN) or U-Net architectures to enhance the detection of fragmented urban fringes and subtle wetland transitions.
- High-Resolution Monitoring: Utilizing CubeSat constellations (e.g., PlanetScope) or UAV (Drone) photogrammetry could provide daily monitoring and sub-meter precision for localized erosion and soil moisture analysis.
- Hydrological Modeling: Integrating LULC data with climate change scenarios and groundwater modeling is essential to predict the future viability of the depression's wetland ecosystem under various drought conditions.
- Socio-Economic Drivers: A multi-disciplinary approach incorporating socio-economic data would help clarify the direct links between population migration, economic shifts, and the rapid land-use conversion observed in the Najaf periphery.

Recommendations

Based on the quantitative findings and the identified environmental trajectories of this study, the following actions are recommended to ensure the sustainable management of the Bahr Al-Najaf depression:

1. Strict Urban Zoning and Buffering: Local authorities should enforce rigorous zoning regulations to curtail the 192% expansion trend of built-up areas. Utilizing the DTM-derived topographic constraints, a "non-development buffer zone" should be established along the eastern cliff-belt to prevent further encroachment into the ecologically sensitive depression floor.
2. Integrated Water Resource Management (IWRM): To mitigate the effects of the observed hydrological instability, immediate strategies are required to regulate groundwater extraction. Establishing a "minimum ecological flow" is essential to sustain the remaining Shallow Water and Wet Soil habitats, which are critical for regional biodiversity.
3. Advanced Environmental Monitoring Systems: A permanent GIS-based monitoring unit should be established, utilizing the Random Forest classification framework developed in this study. Continuous tracking via multi-sensor satellite data (Landsat and High-Resolution imagery) will enable the early detection of illegal land conversion and rapid desiccation events.
4. Legislative and International Recognition: Accelerating the designation of Bahr Al-Najaf as a protected national park or a RAMSAR site (Wetland of International Importance). This legislative protection is vital to safeguard its status as a sanctuary for 168 bird species and to stabilize the local micro-climate against regional desertification.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

I used AI-assisted tools (specifically, a large language model, Gemini) were utilized solely for improving the clarity, coherence, and professional tone of the manuscript's English prose. AI was not used for generating data, conducting analysis, or interpreting results. Its application was restricted to the refinement of existing content prepared by the authors. Key sections where AI assisted in language editing include the Abstract, Introduction, Methodology, Results discussion, and Conclusion. All scientific content, data, and conclusions remain the sole responsibility of the authors.

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Author contributions

Emad A. Al Helaly conceived the research idea, designed the methodology, performed the supervised classification and change detection analysis, and wrote the original draft manuscript. Ali H. Al Rammahi provided critical review, technical consultation on hydrological interpretation, and supervised the overall research. Israa J. Muhsin managed the data acquisition and pre-processing, conducted the accuracy assessment and validation, and contributed to the review and editing of the manuscript.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Suppl. table S1

Authors: Emad A. Al Helaly, Ali H. Al Rammahi, Israa J. Muhsin

Data type: xlsx

Explanation note: This file contain the results of the five features which were selecected to descibe the changes in the study area.

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